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# Infrasound Studies for Yield Estimation of HE Explosions

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Southern Methodist University is conducting investigations to determine the yield of HE explosions from infrasound signals. In particular SMU is investigating how the period and amplitude of infrasound signals scales with the yield of HE explosions. To date there has been little work on this particular topic involving small HE explosions. Studies have been conducted by the nuclear monitoring community on nuclear and large chemical explosions ranging from less than a kiloton to tens of megatons. Our main goal is to develop amplitude and period scaling relationship at local and regional distances (within the so-called zone of silence), extend the relationships to greater distances and create a database of ground truth events. The ranges of the explosions used in this study are from 500 kg to 60 tons of TNT equivalent, well below the previous yield ranges.

Our approach to this effort is to thoroughly study infrasound signals from a well calibrated source in Nevada, develop trial relationships and then extend the results to other ranges and yields. The current annual report covers half of the total performance period.

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# 1. SUMMARY

Southern Methodist University is conducting investigations to determine the yield of HE explosions from infrasound signals. In particular SMU is investigating how the period and amplitude of infrasound signals scales with the yield of HE explosions. To date there has been little work on this particular topic involving small HE explosions. Studies have been conducted by the nuclear monitoring community on nuclear and large chemical explosions ranging from less than a kiloton to tens of megatons (Stevens et al 2002, Pierce and Posey 1971, Clauter and Blandford 1998, Whitaker 1995, references discussed in Mckisic 1997). There were a handful of other technical reports that studied the effects of blasts, for damage assessment purposes (ANSI, 1983; Douglas 1987). However, these technical reports dealt mostly with the behavior of the overpressure at very short distances, and it does not address the problem of scaling at regional distances (within the so called zone of silence). Our main goal is to develop amplitude and period scaling relationship at local and regional distances, extend the relationships to greater distances and create a database of ground truth events. The ranges of the explosions used in this study are from 500 kg to 60 tons of TNT equivalent, well below the previous yield ranges.

Our approach to this effort is to thoroughly study infrasound signals from a well calibrated source in Nevada, develop trial relationships and then extend the results to other ranges and yields. The current annual report covers half of the total performance period.

# 2. INTRODUCTION

This section provides some background and introductory material. In Section 3 we present the methods and procedures used to develop scaling relationships, Section 4 contains preliminary results and discussion while preliminary conclusions are discussed in Section 5.

## 2.1. Source

The Nevada Seismic Array (NVAR) was installed by Southern Methodist University (SMU) in December 1998, near the village of Mina, NV. The array is composed of 10 short period seismic elements with an aperture of 4 km. Collocated with the central four seismic elements (NV01 to NV04) is an infrasound array (NVIAR) roughly 1 km in aperture, initially installed and operated under a University supported research program. NVIAR began operations at the same time as the seismic array. After the installation signals from an army munitions disposal facility were routinely recorded. Figure 1 shows the approximate location of the array and detonation site (dubbed “New Bomb”), located approximately 36 km from NVIAR, and a typical infrasound recording obtained at NVIAR. The recorded signals are usually a suite of five to ten seismo-acoustic signals of 2-4,000 lbs TNT equivalent, spaced at an irregular interval ranging from 40 seconds to 1 minute. This pattern of multiple shots eases the detection problem considerably. Cooperation with the officials in charge of detonation is excellent. They have released weights, videotapes and exact GPS location of the disposal pits. Detonations take place continuously from March to December/January, and in an 18 month period (June 2009 – December 2010) we had over 200 operational days. Because of the existence of the seismic array in the vicinity we were able to determine very accurate origin times of the detonations, within a fraction of a second from a calibrated seismic travel time. The seismic travel time was calibrated against GPS synchronized video recordings of the detonations (Negraru et al 2010). This allows us to calculate very accurate infrasound travel times. We primarily use this source, extremely well calibrated, to address the issue of infrasound scaling relationships. Once trial scaling relationships are developed we will extend the research to other infrasound sources. We have observed in the past at NVIAR, infrasound signals from single fired explosions detonated at the Utah Test and Training Range. This source will provide the upper limit of yield in the scaling relationship (up to 60 tons TNT equivalent). Other sources that are available to us have intermediate range 5-20 t. They include the Israeli infrasound experiments, surface explosions from White Sands Missile Range (WSMR) that reside in our archive and Finnish army munitions disposal activities.

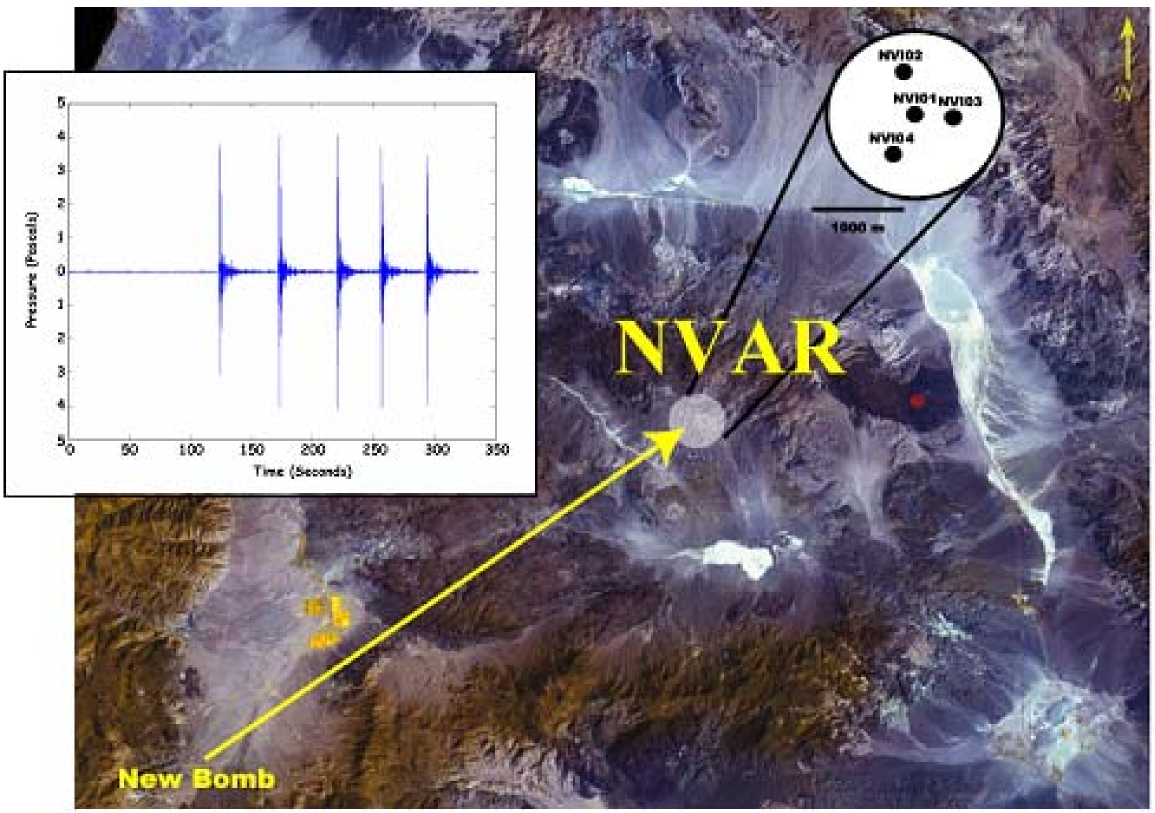


Figure 1. Location of NVAR and the ammunition disposal site (New Bomb). Also shown are the NVIAR configuration and a typical NVIAR recording of the detonations.

## 2.2. Datasets

During 2009 Southern Methodist University installed two small aperture 4 element infrasound arrays to monitor the disposal activities at New Bomb. The first array was installed in June 2009 near Fallon NV, approximately 154 km. north of New Bomb. The second array was installed at the end of October 2009, 293 km. south-east of New Bomb, near Mercury NV. The arrays were called accordingly FNIAR and DNIAR (from Desert Rock NV the name of the NOAA weather station where the array is located). Since the first array started operating until the end of 2010 there were more than 1600 explosions at New Bomb in 224 operating days. However due to the timing of the individual explosions each day we are not able to use all of them in our yield studies (see the paragraph about technical approach).

Two experiments were carried out in June 2009 and December 2009 to better understand the propagation of infrasound in the so called “Zone of Silence”. These propagation experiments were multipurpose and we can also use the acquired datasets for yield study purposes. During these experiments we deployed a total of sixteen infrasound sensors in a line at distances from 20 to 276 km. Both deployments lasted a week. The locations of the arrays and the single stations are shown in figure 2. During the first experiment we placed 14 single infrasound sensors at distances ranging from 23 to 176 km (spaced about 10 km apart) north of the detonation site. We also had two more observation points within 3 km of the source. The second experiment consisted of a similar deployment with instruments spaced about 20 km apart. Unfortunately, due to weather conditions New Bomb operated only a single day in that week.

Other datasets that we proposed to use in the current research project are of larger yield explosions recorded at greater distances, such as the motor rocket detonations at the Utah Test and Training Range, munitions disposal detonations in Finland and the large calibration experiments from Israel.

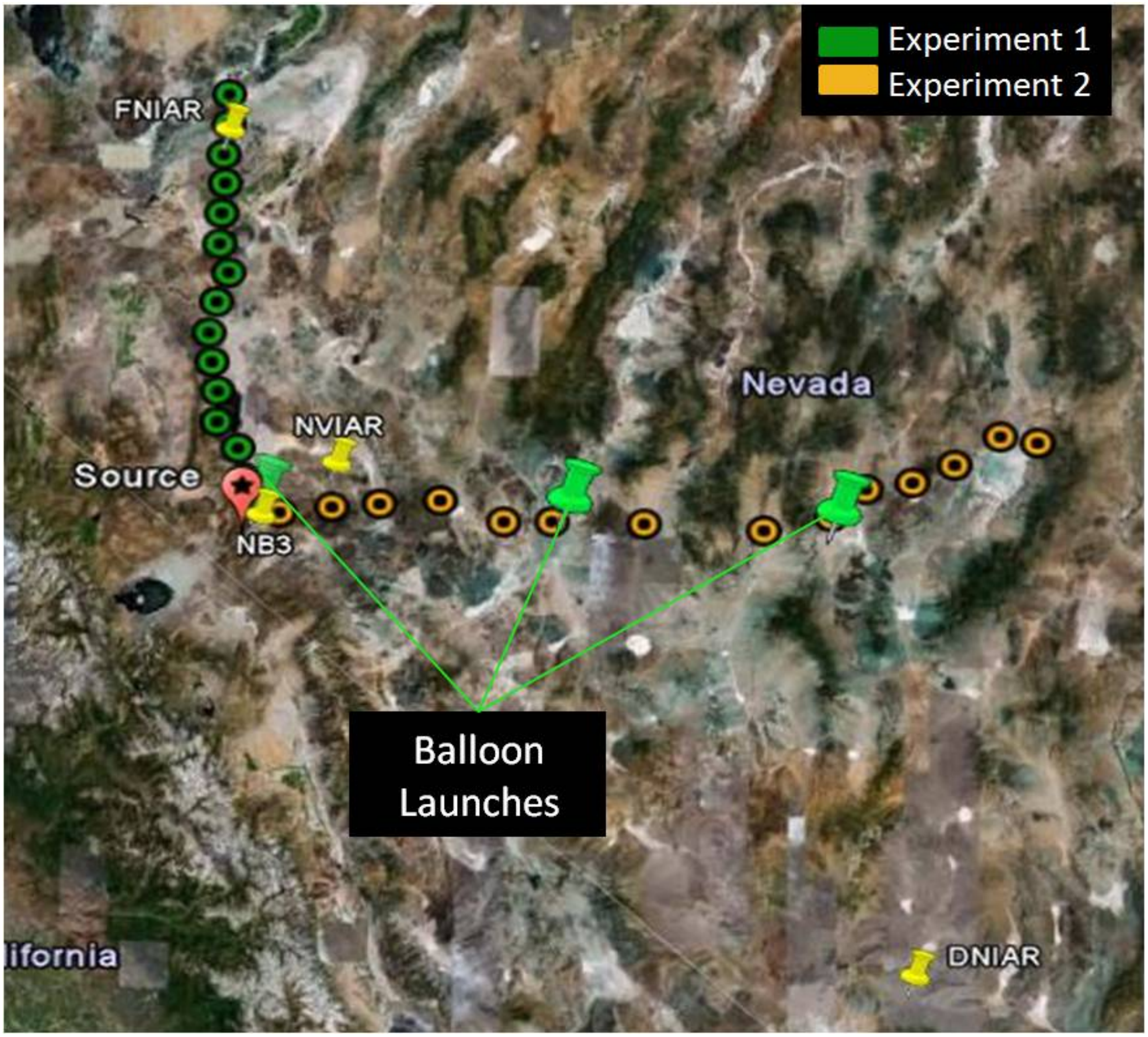


Figure 2. Locations of the two semi-permanent arrays (FNIAR and DNIAR) and the two, week long field experiments.

## 2.3. Nature of the DNIAR and FNIAR observations

Figure 3 shows the observed celerity values (celerity is defined as distance divided by the travel time) for both FNIAR and DNIAR. The detection rate for FNIAR is extremely high (typically around 90%) throughout the whole year. Non detections at FNIAR are usually associated with high local noise conditions or lower source strength (lower yield explosions). DNIAR had a 100% detection rate during winter months, while the detection rate dropped to about 20% in summer months. The most numerous type of arrival is stratospheric. At FNIAR 79% of the arrivals are stratospheric and only 21% are tropospheric. At DNIAR 61% of the arrivals are stratospheric, 24% of them are tropsopheric, and 15% are thermospheric arrivals.

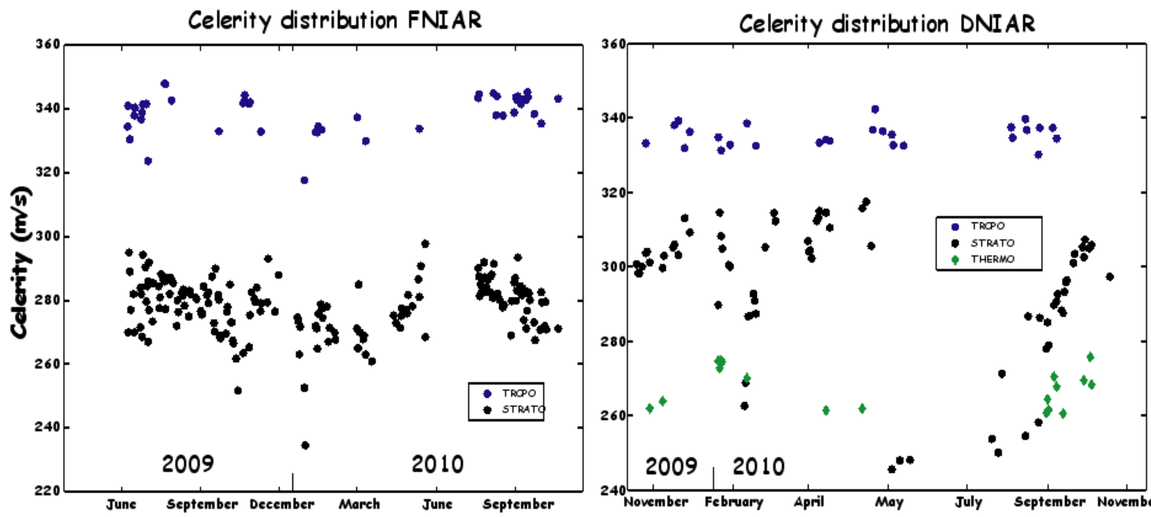


Figure 3. Observed celerity values for DNIAR and FNIAR.

No seasonal celerity pattern is observed for FNIAR (figure 3, left), while DNIAR exhibits strong seasonal variations (figure 3, right). This is expected as the source to receiver azimuth is due north at FNIAR thus affected by the moderate predominantly favorable meridional winds, while DNIAR is east of the source and affected by the seasonal east-west stratospheric zonal winds. Typically winter stratospheric celerity values at DNIAR range from 290-315 m/s. Both arrays record extremely low celerity values at times when the stratospheric wind jet is highly variable (January-February). The change to summer conditions is sharp, and is characterized by celerity values between 240-260 m/s, and an absence of one of the late arrivals. To fully determine the nature of the 3rd winter arrival or the late summer arrival we need to attempt atmospheric modeling, but this is beyond the scope of the current project. However, we focused our research study on the tropospheric and stratospheric arrivals which are by far the most numerous types of arrivals. The change back to winter conditions shows a gradual increase in the stratospheric celerity. From mid-September the third arrival (either thermospheric or high stratospheric arrival) is observed again. Tropospheric arrivals are not affected by the seasonal variations, and occur throughout the whole year. Typically the stratospheric celerities are much lower at FNIAR than DNIAR, though the array is much closer to the source. In terms of amplitudes the DNIAR stratospheric arrivals are much higher amplitudes than DNIAR, while the tropospheric arrivals exhibit larger variability.

## 3. TECHNICAL APPROACH

The first step in calibrating infrasound scaling relationships is to determine how well the ground truth information is known. The origin times of explosions are known within a fraction of a second, The weight of the disposed material is well known, but actual yield variations due to different explosivity characteristics of the material are not exactly known. The officials in charge of the disposal facility keep and provide us with detailed logs of the detonations with the weights of the material disposed. Therefore, due to the very large amount of data (more than 1,600 explosions in a 18 months period) we decided to calibrate a weight/seismic relationship. The calibrated relationship at NV08 given in figure 4 is:

$$\log(WEIGHT) = \log(RMS) + 2.18$$

where *WEIGHT* is the weight of material detonated in a single shot in lbs. and the RMS is the observed root mean square (*RMS*) value in nm for a the first 20 seconds of the seismic signal observed at NV08.

The smallest weights in the figure are 868 lbs, while the largest are a little below 4,000 lbs, but there are no points between 868 and approximately 1,800 lbs. Explosions in this range are usually misfires and therefore no weight information is available. The error of the fit is approximately 10%. Preliminary analysis of the seismic data suggests variations in actual yield (due to material explosivity) are about 10%.

The multiple shot pattern that eases the detection problem considerably contaminates the later detonation signals with energy from the coda of the earlier ones. Also only the first two seismic detonations are clear of the effects of the air pulse which couples locally as Rayleigh waves. Even if we had accurate determination of the later shots, a similar contamination is observed at FNIAR quite often, and it is extremely difficult to separate the individual detonations. Therefore we use only signals from the first explosion in our yield studies.

Due to propagation effects that make the determination of the dominant periods difficult (particularly for the close in array) we decided to acquire near source waveforms to help us in the identification of the dominant period at regional distances. From August 2010 through November 2010 all the shots detonated at New Bomb consisted of exactly 3,500 lbs of C4 plastic explosives. During that time we recorded signals using a single low sensitivity infrasound sensor capable of recording the high pressures, inside the non-linear region of the source approximately 700 meters from the nearest explosion pit. After analysis of these so-called N-waves, we determined that the variation in yields of these shots was only about 5%. This is a factor of two better than the actual precision that we inferred from the seismic recordings, and much better than the 20% variation in yield that is usually encountered (and accepted) in literature.

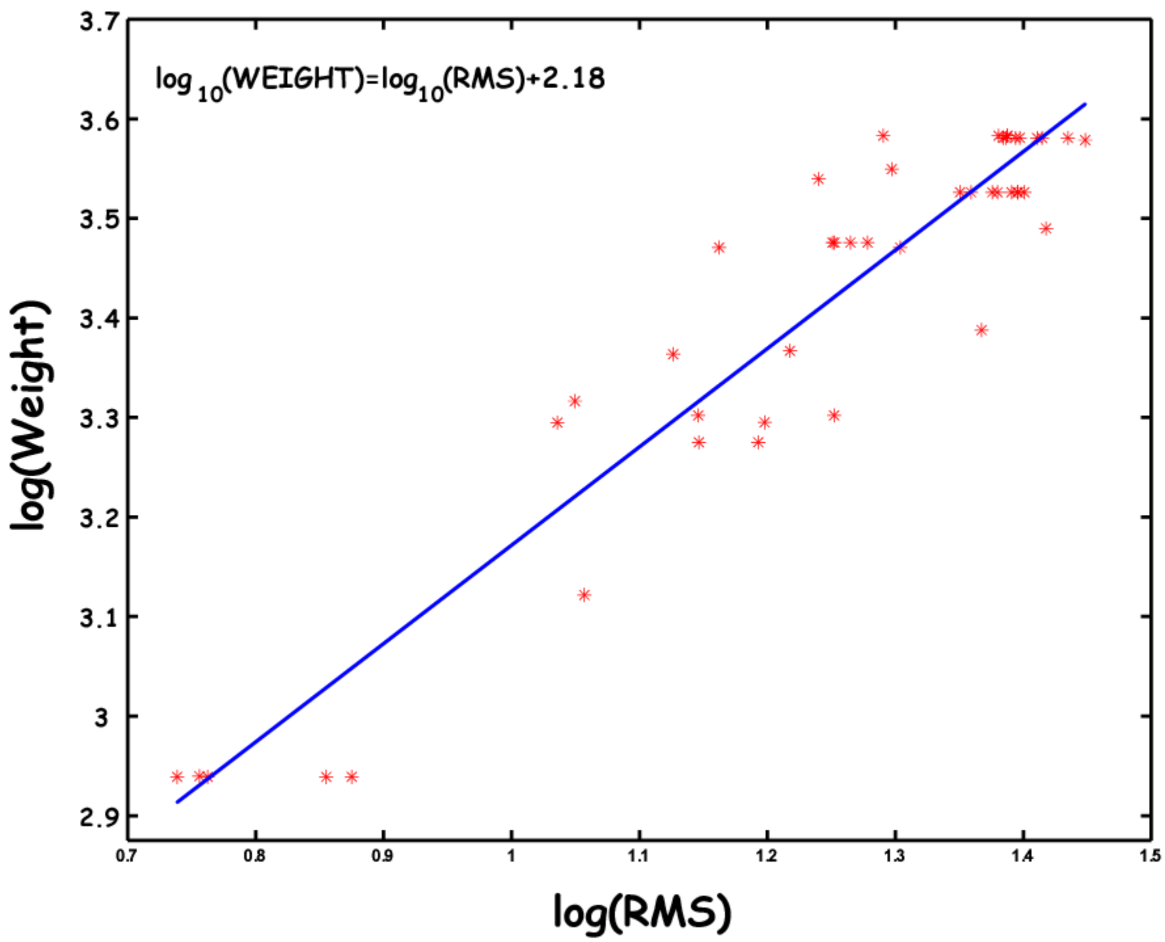


Figure 4. Weight (in lbs.) plotted against root mean square observations at NV08 (in nm). The blue line is the least square fit to the data.

We have analyzed all the signals from the 3500 lbs. detonations that were observed at FNIAR and DNIAR with a variety of techniques (Fourier based and autoregressive based methods). Due to probable multipathing it is extremely difficult to pinpoint a dominant frequency in the dataset, and it was necessary for us to empirically try several different orders in the AR method for the same signal. Usually a dominant peak in the frequency appears for all techniques. The mean dominant frequency of all observed stratospheric arrivals was 1.24 Hz, with a standard deviation of 0.21 Hz (and a sample size of 32). The empirically determined AFTAC formula (Armstrong, 1998) for yield shows that the yield is proportional to the period to the 3.34 power. As we don't yet have the ranges to determine the actual slope of the yield/period relationship we will initially use this slope. In the second phase of the proposal we will attempt to calibrate the slope once we integrate other sources of different yields. If we use a mean value of 1.24 Hz for the 3,500 lbs shots we obtain the following yield/period formula:

$$Y = C\,T^{3.34}$$

Where Y is the yield in lbs., C is a constant and in this case is 7,180 and T is the period in seconds. The 90% confidence interval for the sample mean and the given standard deviation range from 0.415 to 0.577. This would translate to a range of yields from 2980 to 4142 lbs.

During the same period we observed 13 tropospheric arrivals. Their mean dominant frequency was 1.68 Hz but the standard deviation was 0.61. Using the same approach that we used for stratospheric arrivals we obtain a range of yields from 2099 to 6404 lbs. This error is much higher than that obtained for the stratospheric arrivals. Typically we have observed that the dominant peaks of the tropospheric arrivals are higher frequency than the stratospheric arrivals, and therefore the constant used in the above formula must be different for stratospheric and tropospheric arrivals. We also note that in the calculation of the confidence intervals we have assumed a normal distribution of the populations. Recent work assumed that the departures from the long term propagation models such as G2S are Gaussian (the background noise is Gaussian). If this is the case we can safely assume Gaussian distribution for our case, but this assumption has not been confirmed.

DNIAR data exhibits strong seasonal variations (see the discussion from the technical approach), therefore the procedure that was employed at FNIAR for stratospheric arrivals was not possible here for thermospheric or stratospheric arrivals. Only seven tropospheric arrivals were observed at DNIAR for this period of time and one of the arrivals is clearly an outlier. It exhibited a clear dominant peak at 3.7 Hz, much higher than anything encountered before.

# 4. PRELIMINARY RESULTS

This section describes our current progress on calibrating a period/yield relationship and on amplitude scaling with distance. Accordingly it is broken into two subsections.

## 4.1. Period/Yield relationship

Considerable effort in the last two quarters was devoted to calibrating a dominant period/yield relationship. The main difficulty in developing a relationship resides in the complexity of the observed stratospheric signals making the determination of the dominant period extremely difficult. This is particularly true for FNIAR signals where the observed stratospheric arrivals appear to be contaminated by overlapping delayed signals which may or may not have the same dominant frequency. This leads to complex spectra that are difficult to interpret. There could also be tropospheric/stratospheric interference that could make the observation of the onset of the stratospheric arrivals difficult. The spectra of the signals observed at DNIAR are easier to interpret, but they also exhibit interference. The signals that were obviously contaminated or exhibited interference were not used in our preliminary yield/period relationship. Out of the 169 stratospheric arrivals at FNIAR we were able to use 101, at DNIAR we used 49 out of 70.

We have used a variety of methods in our attempt to determine the dominant period as accurately as possible. After filtering the data with a 2$^{nd}$ order Butterworth filter from 0.5 -5 Hz and correcting for the instrument response we applied both the autoregressive technique and Fourier based methods to determine the dominant period. In the cases in which the signals had short durations the resolution in the frequency domain was poor but we obtained good results using a low order AR technique (order 8). However, in the case of complex signals even high order AR techniques (order 48) did not provide a good representation of the spectrum. In general AR techniques had comparable results with the Fourier based methods.

In figure 5 we show the dominant period/yield relationship and the least squares fit for the stratospheric arrivals observed at both stations. While the standard error of the estimate is relatively small the error is much larger for the low yield explosions. The previous empirically calibrated yield/period relationship showed that the yield of an explosion is proportional to $T^{3.34}$, while for both arrays we obtained an exponent of around 0.5. It should be noted that the yields (weights) of our explosions span from 900 to 4,000 lbs. (a factor of four) while other relationships were developed from a dataset that spans five orders of magnitude from 0.1 Kt to 10 Mt. A second problem could arise from the fact that there are only a few low yield explosions and we detected only a small fraction of those. Also DNIAR was not installed when the largest and the lowest detonations occurred. The large majority of the observations are typically above 3500 lbs. Therefore our data are still insufficient to determine whether the relationship breaks down at low yields, but extending the study to include other sources of higher yields (such as UTTR explosions or the large calibration experiments from Israel) might clarify this matter. Also our data suggest that at least for these distance ranges (154-295 km) there is no need to correct for a frequency dependent absorption which would lead to a decrease in frequency at larger distances. This may not be the case for long range propagation.

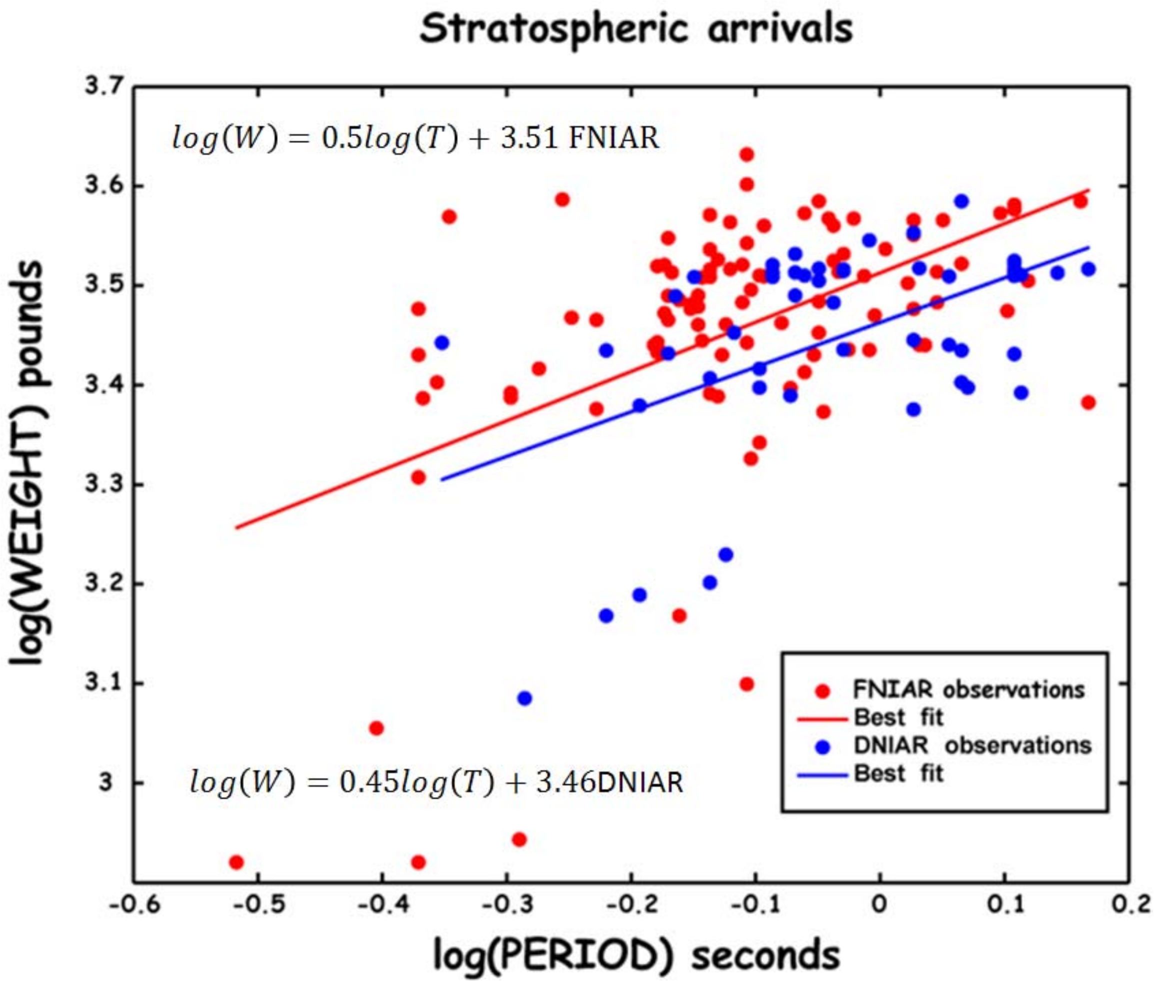


Figure 5. Dominant period/yield relationship for FNIAR and DNIAR.

The tropospheric arrivals are usually monochromatic and they exhibit only one arrival, therefore we know the dominant period with a higher degree of confidence. However the results are contradictory. For instance at FNIAR we have observed higher frequencies for the larger detonations and this suggests that the observed dominant periods may be related to propagation, perhaps to the thickness of the inversion layer in combination with topographic effects.

### 4.2. Amplitude scaling studies

To study the amplitude scaling relationships we need observations at different ranges and therefore a field experiment was carried out in June 2009 during which single infrasound sensors were deployed in a northerly direction at distances ranging from 2.5 to 176 km from the source.  During the four days in which atmospheric data was collected we had great variability in the meteorological data.  Figure 6 shows the effective sound speed profiles built from the actual meteorological measurements and the corresponding rays.

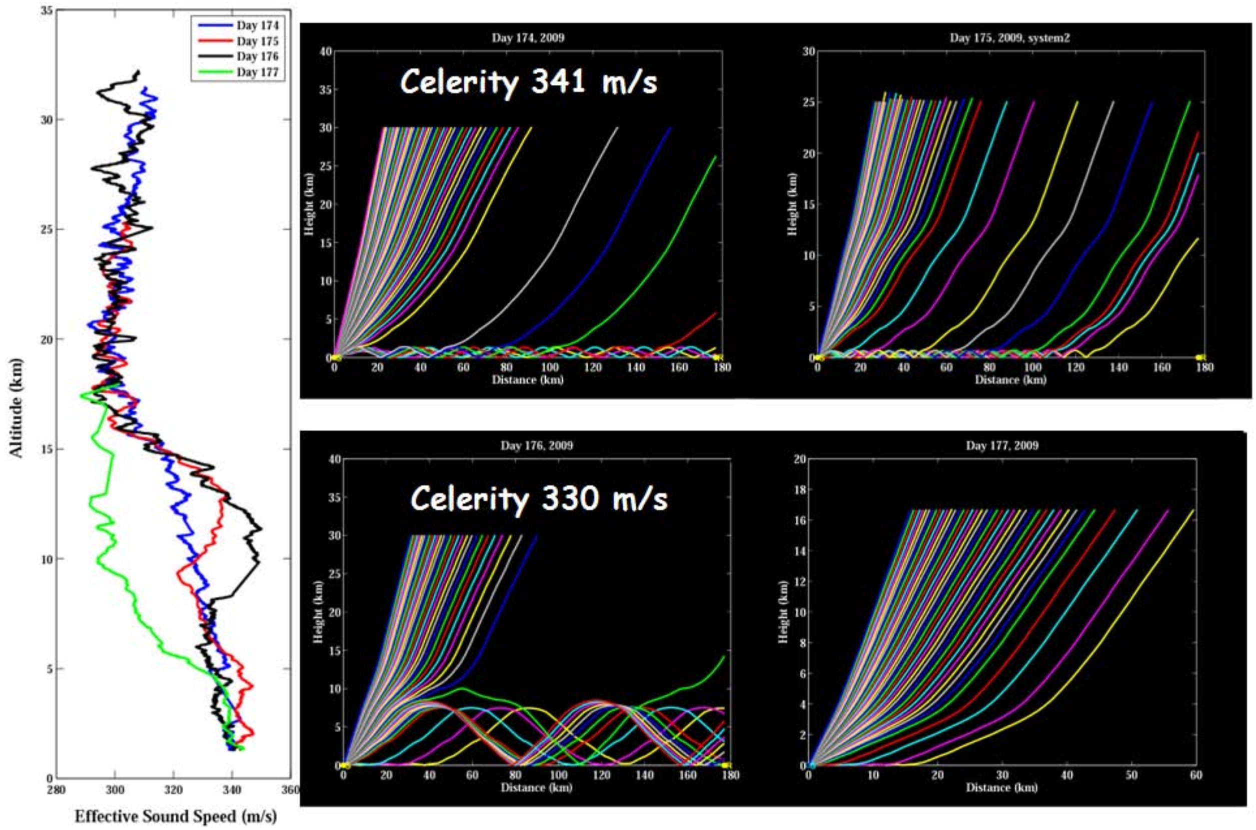


Figure 6. Effective sound speed and corresponding rays for a line of sensors deployed north of the New Bomb site to 176 km.

The figure shows there is an inversion layer between 8 and 12 km we believe to be due to the jet stream during Julian day 176, while during the rest of the days raytracing suggests the observed arrivals propagated in near surface ducts. No stratospheric arrivals were observed except for the last day and those occurred at distances over 154 km. Due to the proximity of the sensors to highways this dataset is relatively noisy and it was difficult to identify the actual arrivals at all stations. Figure 7 shows the observed amplitudes of the tropospheric arrivals and the least square fit through the dataset. All the detonations were 3809 lbs of mixed ordnance. What is interesting is that the amplitudes of all arrivals observed from the low altitude duct decay in the same way, while the jet stream propagation is affected by focusing and defocusing effects.

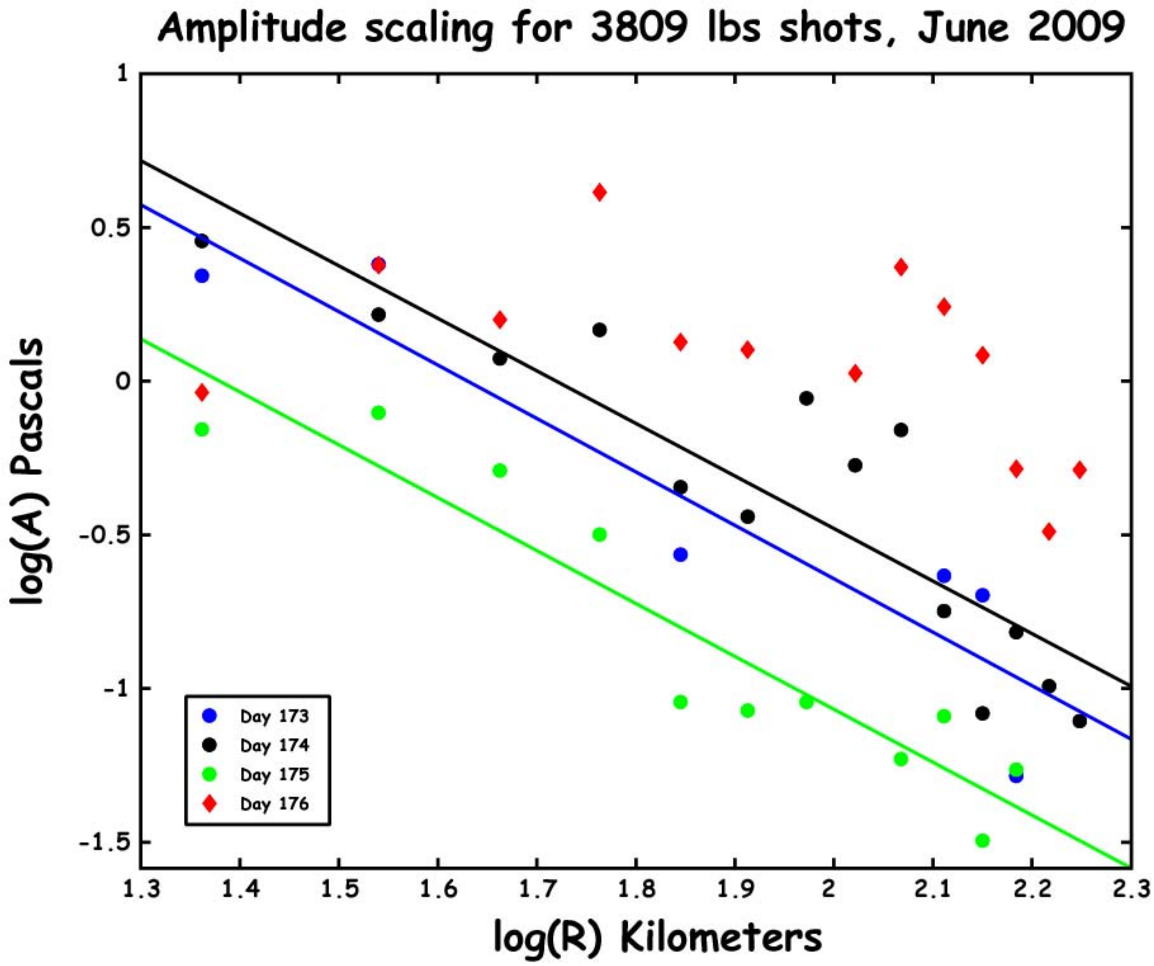


Figure 7. Amplitude versus range for 3809 lbs of mixed ordnance.

There are several scaling relationships that were published in literature that we applied to our dataset. Some of them were summarized in a paper by Stevens et al 2002:

$\log(P) = -1.54 + \log(W) - 0.5\log(R\sin\Delta)$, Pierce and Posey

$\log(P) = 0.92 + 0.5\log(W) - 1.47\log(\Delta)$, Clauter and Blandford, 1998

$\log(P) = 3.37 + 0.68\log(W) - \log(R)$, LANL formula

$\log(P) = 3.00 + 0.33\log(W) - \log(R)$, used by Russian scientists

Where P is the zero to peak pressure in Pascals, W is the yield in kt, R is the distance in km and $\Delta$ is the distance in degrees.

All formulas were developed from datasets of nuclear explosions and therefore we applied a correction for the chemical energy release. Considering that a chemical explosion releases half of the energy released by a similar yield nuclear explosion we have applied the following correction:

$$\log(P_C) = \log(P_n) - \log(2)$$

Where Pc is the pressure observed from a chemical explosion and Pn is the pressure observed from a nuclear explosion.

A second correction applied is the wind correction. The role of the formula is to correct observed pressure to zero wind conditions. The correction is:

$$\log(P_{cor}) = \log(P_{raw}) - 0.018V_d$$

where $P_{cor}$ is the corrected zero to peak pressure amplitude, $P_{raw}$ and $V_d$ is the maximum wind in the propagation direction.

The results for these relationships are shown in figure 8. The best result is obtained by the Clauter and Blandford formula, while Pierce and Posey is completely off scale. Stevens found that the Pierce and Posey formula, a theoretical derivation for the Lamb edge excitation fits relatively well with Lamb waves observed for very large nuclear explosions (yields larger than 1 Mt), but performed poorly for the rest of their dataset. The slope of the LANL formula is closer to the best fit line as opposed to the formula used by Russian scientists, who consider the pressure to be proportional to the cube root of distance. The LANL formula was derived empirically on a dataset of stratospheric arrivals and makes use of wind corrected amplitudes, while our dataset is composed of only tropospheric arrivals.

However let's consider the general form of the ANSI relationship (ANSI, 1983):

$$A_0 = C\left(\frac{R}{W^m}\right)^p$$

Where $A_0$ is the amplitude, W is weight (or yield), R is the distance and C, p and m are proportionality constants. If we take the logarithm of the above relationship any of the empirical or theoretical formulas used above can be obtained for a particular set of constants, therefore attempting to use the LANL formula at least for illustration purposes is appropriate.

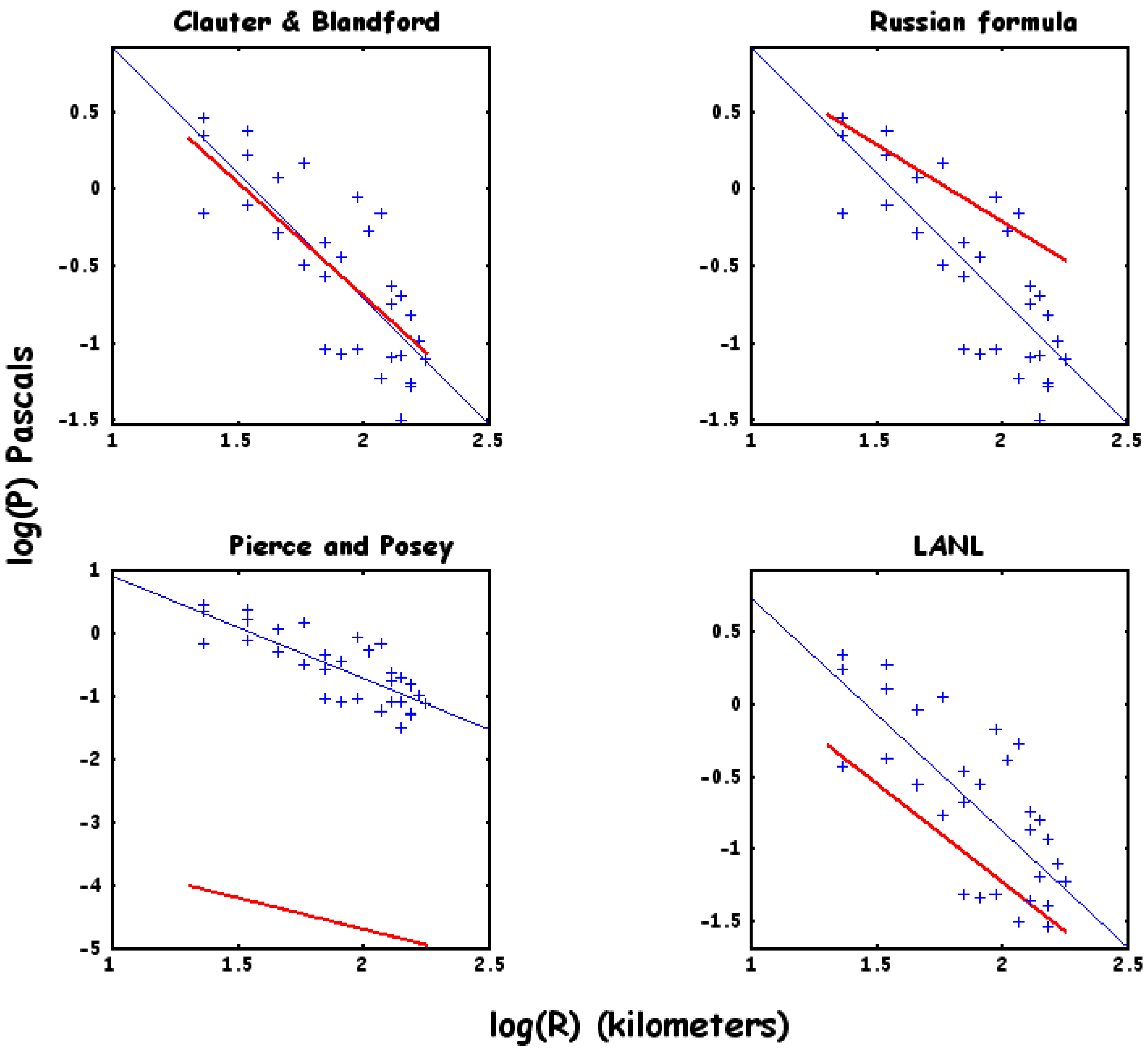

Figure 8. Wind corrected amplitude versus range observations and best fit. Also shown are the estimates using different formulas.

Figure 9 shows our best fit starting from the ANSI relationship. Our approach was a little different than the previous scaling studies in that we determined the p values empirically taking advantage of the fact that all detonations are of similar yield. Therefore a $log(A_0)$ versus $log(R)$ plot would find the $p$ value, assuming that W is constant. The value for p that we determine empirically is -1.63, and is a little different than what is usually inferred for p (-1.2 to -1.5). Differences in the constants are usually explained in variations of the wavefront geometry (spherical versus cylindrical wavefronts) corresponding to near and far field observations. Future work will attempt to use the constants derived empirically for other sources.

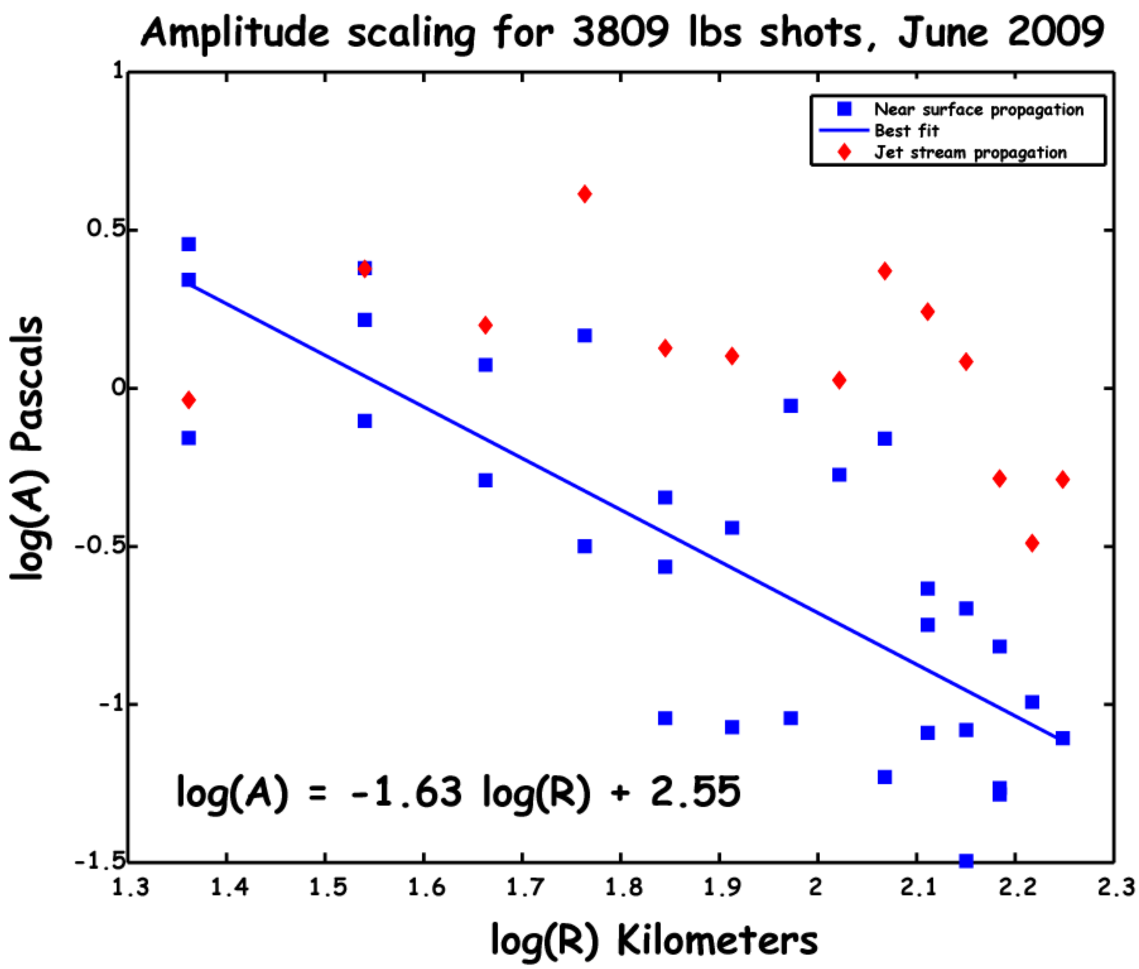

Figure 9. Regression of the dataset for near surface propagation.

We have also used the Blast Operational Overpressure Model (BOOM) of Douglas 1987, to match our observations. The model is applied at distances of 5-50 km and is used to predict the amplitudes of the overpressure. The BOOM relationship is defined in terms of a weather parameter B as follows:

$$L = 103.1 + \frac{B}{5.3} + 20 \log\left[\left(\frac{S}{1013}\right)^{0.556}\left(\frac{W}{110}\right)^{0.444}\left(\frac{25}{R}\right)^{1.333}\right]$$

where

$$B = \text{arctangent}\left[3\left(\frac{\Delta V}{\Delta Z}\right)\left(\frac{R}{C}\right)\right]$$

The relationship is dependent on the parameter B (in degrees) which takes into account the atmospheric conditions at the time of the detonations. $\Delta V$ (m/s) is the maximum difference in the sound speed and the surface sound speed and $\Delta Z$ (km) is the altitude at which $\Delta V$ is observed, C is the sound speed at the surface (in m/s), R is the distance to location of interest (km), S is the surface atmospheric pressure (mbar), W is TNT equivalent of explosive weight (in kg) and L is the maximum overpressure expressed in dB. The conversion factor from dB to Pascals is given by:

$$PK = 0.00002 * 10^{(L/20)}$$

Where PK is the pressure expressed in Pascals. The results are shown in Figure 10.

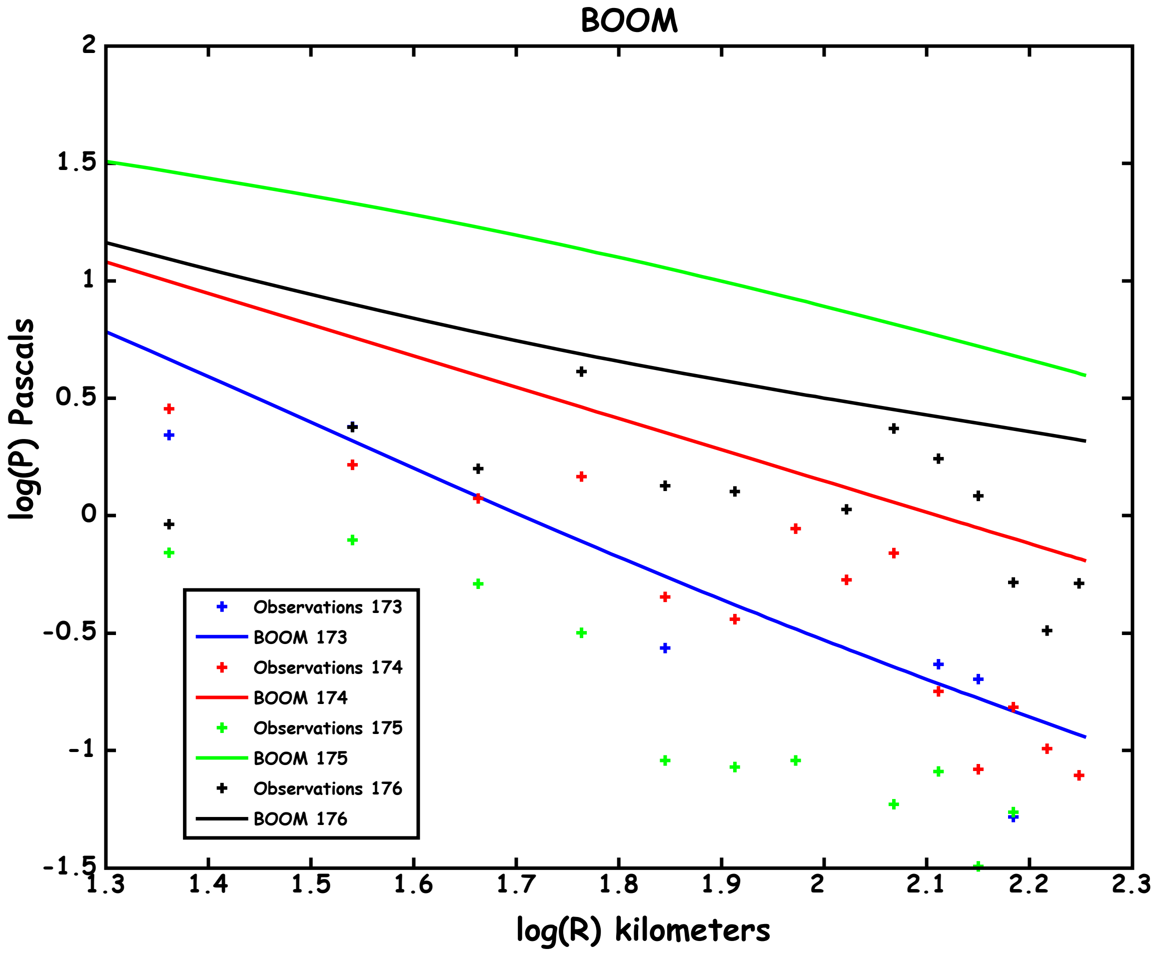

Figure 10. BOOM against New Bomb observations.

In this case we also show the values for day 176 as the B parameter takes the atmospheric conditions into account. For day 176 we used jetstream values for $\Delta V/\Delta Z$, while for the other days we used the maximum sound speed in the first few km of the troposphere. The difference between the results and the observations suggests that our knowledge of the actual meteorological conditions near the surface are not as well constrained as BOOM requires. This may be because the balloon launches were at the Hawthorne airport, about 35 km away from New Bomb and about 500 m difference in altitude between New Bomb and the airport.

## 5. CONCLUSIONS

The second year of our study will focus on expanding the dominant period/yield relationship to larger yields and ranges. A rigorous study of stratospheric amplitudes at FNIAR and DNIAR has not yet been performed and we plan to undertake those efforts. We have access to G2S models and they should constrain the stratospheric winds relatively well. Note that when the LANL formula was derived G2S models were not available and the current models show that the actual peaks in the stratospheric winds are above 50 km. Therefore the LANL formula should be updated with the current more detailed models. Unfortunately we do not have stratospheric observations at many ranges, but we have a very large number of observations at two specific distances. We will be able to observe if and how the amplitudes are being affected

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# List of Symbols, Abbreviations, and Acronyms

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| AFRL | Air Force Research Laboratory |
| AFWL | Air Force Weapons Laboratory |
| LANL | Los Alamos National Laboratory |